USE OF WATER DEMAND AND CONSISTENCY PREDICTION MODELS AS STEERING ELEMENTS FOR THE PRODUCTION OF CONCRETE

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ABSTRACT

The diagrams of Powers allow us to understand and to predict the voids ratio of particle mixtures. The general theory of Dewar for particle mixtures and the implementation of the voids ratio diagrams of Powers in this theory are explained. The basic water demand of the concrete mixture is derived from the theory of particle mixtures and a consistency prediction model is used to calculate the water demand of the concrete mixture. By using the voids ratio diagrams of Powers, the theory of Dewar for particle mixtures, and a systematic follow up of the parameters of the raw materials, a reliable water prediction model can be obtained. Consequently this model enables to make accurate consistency and strength predictions, which can be used in mix design and mix proportioning in order to steer the concrete production.

In this contribution a case study is provided, based on data from Belgian ready mixed concrete plants. The influence of the variation of the mean size and the voids ratio of the cements, fine and coarse aggregates as well as the variation in grain size distributions on the water demand of the concrete is analyzed. Based on the variation in the constituting materials, the variability of the water demand is estimated based on Monte Carlo simulation techniques. Further, this result is compared to the variation of the water demand based on the analysis of strength results.

Keywords: Ready Mixed concrete, Water Demand, Consistency, Monte Carlo Simulations

INTRODUCTION

A lot of studies have been performed on numerous models for the prediction of concrete strength. In case of ready mixed concrete however, the water demand and consistency are even more important. Nevertheless, these two characteristics are difficult to predict, because they depend on numerous parameters which are not always fully understood or under control. By using the voids ratio diagrams of Powers, the theory for particle mixtures of Dewar, and a systematic follow up of the parameters of the raw materials, a more reliable prediction model for the water demand of concrete is obtained. This leads to a better prediction and control of the concrete strength and consistency.

VOIDS RATIO DIAGRAMS OF POWERS

The voids ratio diagrams of Powers [1] are essential to understand and to predict the different effects that occur when fine and coarse particles are mixed. To design a voids ratio diagram, the voids ratios of the fine and coarse particles U_1 and U_0 are plotted on 2 opposite vertical axes. The fraction of fine particles is plotted on the horizontal axis (on a volumetric basis).

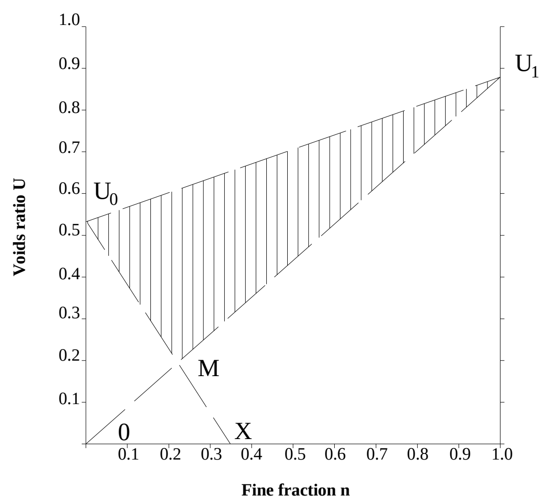

Fig. 1: Voids ratio diagram for a mixture of fine and coarse particles

The line U_0X in Fig. 1 defines the theoretical effect on the voids ratio of the mixture when fine particles are added without any dilatation of the structure of the coarse particles. M is the point where the fine materials fill the voids of the coarse material. The line U_10 defines the theoretical effect on the voids ratio of the mixture when coarse particles are added to the fine particles without increasing the voids ratio of the fine material (fine material is replaced by coarse material). M is the point where the coarse particles come into contact.
The area U_0MU_1 gives all possible mixtures when particle interference is taken into account. The boundary U_0U_1 represents a situation where the mean sizes of the aggregates are the same and interference reaches a maximum.
The voids ratio is calculated using equation (1) or (2).

$$U_n = U_0 - n(1 + U_0) \qquad \text{(in the range } U_0M\text{)} \tag{1}$$

$$U_n = nU_1 \qquad \text{(in the range } MU_1\text{)} \tag{2}$$

The coordinates of M are given by equation (3).

$$n_M = \frac{U_0}{(1 + U_0 + U_1)},\ U_M = \frac{U_0 U_1}{(1 + U_0 U_1)} \tag{3}$$

Investigation of Fig. 1 leads to the following conclusions:

– Experimental data lies in the area U_0MU_1.
– The deviation from the lower boundary is the greatest in the neighbourhood of M.
– Experiments show that results lie closer to the boundary U_0MU_1 when the size ratio r ($r = mean\ size\ of\ \ fine\ particles / mean\ size\ of\ coarse\ particles$) decreases. A high value of r (± 1) gives results which lie near the upper boundary.
– The particle interference has a large influence on the voids ratios of particle mixtures.

THEORY OF PARTICLE MIXTURE AND CONSISTENCY MODEL OF DEWAR

VOIDS RATIO DIAGRAMS FOR REAL MIXTURES OF PARTICLES

Dewar introduced the spacing factor m and the spacing factor *z* to explain the particle interference [2]. When fine particles are added to the mixture, the coarse particles are spaced apart by a value of *m* times the diameter of the fine particles. Therefore the voids ratio of the coarse particles increases from U_0 to U_0''.

The fine particles fill the available space within the dilated structure of the coarse particles. There are boundary effects (wall effects) between the coarse and the fine particles which result in an additional space. This increase can be modelled with a hypothetical zone of $0.5\ z\ D_0$ (with z = spacing factor and D_0 = diameter of the coarse particles) around the coarse particles.

The effects that occur when particles are mixed can be quantified by Dewar's model [2] and are illustrated in a voids ratio diagram (Fig. 2). The voids ratio diagram consists of six points $A - F$ which are connected by straight lines.

Values for the spacing factor *m* for the different changing points in the voids ratio diagram, are given in Table 1. Values for the empirical factors for the calculation of the spacing factor *z* for the different changing points in the voids ratio diagram, are given in Table 2.

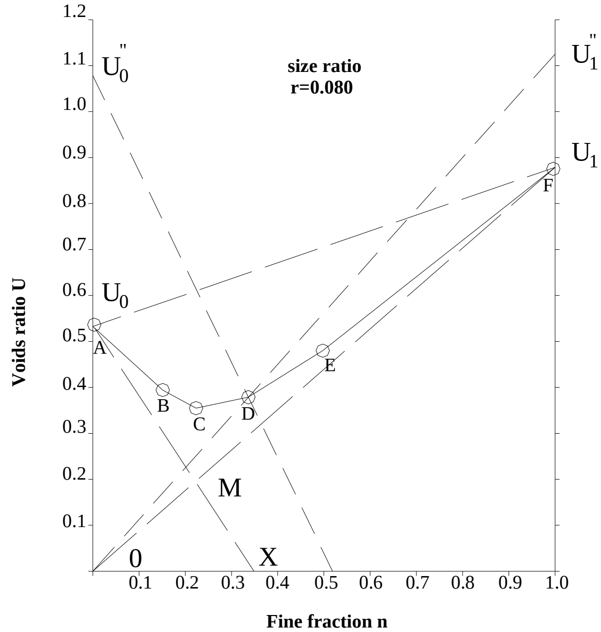

Fig. 2: Voids ratio diagram for real mixtures of particles

Table 1: Values for the spacing factor *m*

Point in	***m***
A (n=0)	0
B	0.3
C	0.75
D	3
E	7.5
F (n=1)	∞

Table 2: Empirical factors for the calculation of the spacing factor *z*

Point in	k_{int}	k_p
B	0.12	0.60
C	0.06	0.65
D	0.015	0.80
E	0	0.90

The coordinates of the points B – E can be calculated and plotted in a graph (Fig. 3) when the following information is available:

- Mean size of the different particles
- Voids ratio of the different particles
- Size ratio of the particles
- Spacing factors *m* and *z*

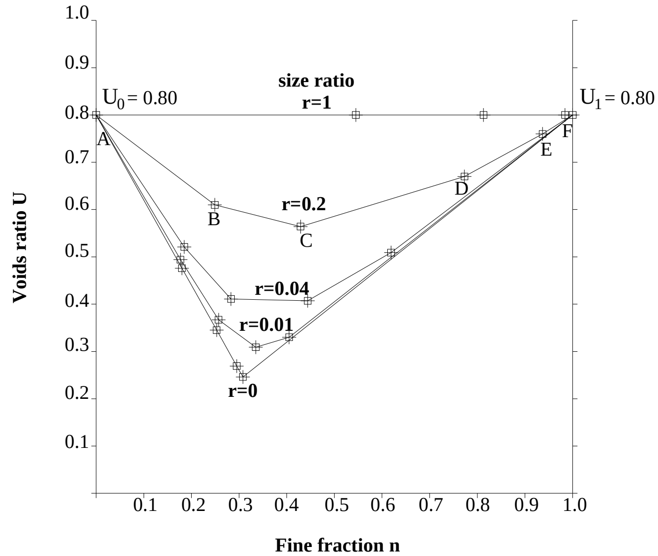

Fig. 3: Voids ratio diagram for real particle mixtures with different size ratios

The empirical and mathematical equations used for the calculation of the points $B-E$ are given in equations (4) to (9).

$$U_0'' = (1+U_0)(1+mr)^3 - 1 \tag{4}$$

$$z = k_{int} + \left[(1+U_0)^{\frac{1}{3}} - 1 - k_{int}\right] r^{k_p} \tag{5}$$

$$U_1'' = \frac{(1+U_1)U_0''}{(1+U_0'') - (1+z)^3} - 1 \tag{6}$$

$$n = \frac{U_0''}{1+U_1''+U_0''} \tag{7}$$

$$U_n = nU_1'' \tag{8}$$

$$S_n = \frac{1}{1+U_n} \tag{9}$$

THE USE OF THE THEORY OF PARTICLE MIXTURES FOR PASTES, MORTARS AND CONCRETES

The theory of particle mixture can be applied on mixtures of powders in water (pastes) [2]. The voids ratio of the powders should be determined in water by using the Vicat normal consistency test [3]. It is possible to combine different powder based materials by using the explained theory. Mixtures of pastes and fine aggregates (sands) result in fresh mortars. Mixtures of mortars with coarse aggregates result in concrete mixtures. It is thus important to determine the parameters of the mortar (at the change points) first. In a second step the

coarse aggregates are added and the parameters of the different concrete mixtures can be determined.
Dewar [2] introduced also a cohesion parameter which makes it possible to adjust the proportion of the mortar in the concrete.

$$n_x = n_{min} + 0.025\,CJ \tag{10}$$

with: - n_{min} volumetric proportion of the mortar solids to concrete at the point of minimum voids ratio
- CJ cohesion adjustment parameter (between 0 and 4, usually 1)

The voids ratio U_x (voids ratio of the point with adjusted cohesion) can be determined using equation (11), based on a linear relationship between each pair of change points. This voids ratio U_x will always be higher then the minimum voids ratio.

$$U_x = \frac{n_x - n_d}{n_e - n_d}\left(U_e - U_d\right) + U_d \tag{11}$$

with: - n_d, U_d the coordinates of the point with the lowest voids ratio
- n_e, U_e the coordinates of the point with a higher n value
- n_x, U_x the coordinates of the point with a good cohesion

Dewar [2] also introduced an empirical adjustment parameter J to link the voids ratio of the mixture to the water content of the concrete.

$$J = k_1 - k_2 D_{fa} \tag{12}$$

with: - D_{fa} the main size of the fine aggregates
- k_1, k_2 constants as given in Table 3 (which are linked to the change points A-F).

Table 3: Values of the empirical constants k_1 and k_2

Point in diagram	$\boldsymbol{k_1}$	$\boldsymbol{k_2}$
A	0	0
B	0.0225	0.015
C	0.0225	0.0525
D	0.015	0.07
E	0.0125	0.07
F	-	0

The adjusted voids ratio at point x can be calculated using equation (13).

$$U_{JX} = \frac{U_X - J(1+U_X)}{1+J(1+U_X)} \tag{13}$$

Based on the previous, the volume of the different materials (cements, powders, fine aggregates, coarse aggregates) in the mix can be calculated.

MODELLING THE CONSISTENCY OF CONCRETE

The concrete mix is designed for a reference slump of 50 mm. The water adjustment for other slump values is nearly independent of the materials and the concrete parameters that are used [2]. The water adjustment parameter F_s for a given slump can be calculated from equation (14).

$$F_S = 1 + \frac{(SL - SL_{ref})}{6(SL + SL_{ref})} \tag{14}$$

with: - F_S adjustment parameter
- SL given slump in mm
- SL_{ref} reference slump in mm (SL_{ref} = 50 mm)

CASE STUDY OF BELGIAN CONCRETE MIXTURES

Most Belgian ready mixed concrete plants produce concrete using empirical recipes, which meet the European Standard EN 206-1 [4]. If the change in water content is known, an accurate prediction of the compressive concrete strength can be made with one of the many available strength prediction models [5]. However, the actual water content of a concrete mixture is depending on various influences (e.g. properties of the raw materials, skeleton, desired slump, weather conditions,…). Furthermore, most of these properties are not or cannot be determined adequately or accurately. As a result of this, the straightforward use of strength prediction models without modelling the change in water demand often results in an unsatisfactory high variability in the production.
By using the voids ratio diagrams of Powers, the theory of particle mixtures and a systematic follow up of the relevant parameters of the raw materials, a reliable system for the prediction of the water demand is obtained. Further, the presented methodology can be also be used for the assessment of dependency of the mixtures towards the variation of constituting materials. In order to illustrate this ability, this paragraph provides a case study based on data obtained from a Belgian concrete plant.
In Table 4 the composition of a concrete mixture from a Belgian ready-mixed concrete plant is given. The discussed models are calibrated on these data.

Table 4: Concrete mixture of a Belgian ready-mixed concrete plant

Mix Design	**[kg/m³]**
CEM III/A 42.5 LA	260
Fly ash	15
Water	170
Sand 0/2	504
Sand 0/4	393
Coarse Aggregates 6/20	954
Water reducer (Sky)	1.62

In order to predict the water demand of the mixture, the mean size and voids ratio of the constituents were determined over a period of one year (Table 5). Based on the limited data, the assumption of a normal distribution for the mean size and voids ratio is justified.

Table 5: Mean and standard deviation of the mean size and voids ratio of the constituting materials

Constituents	**Mean size mean [mm] (st.dev.**	**Voids ratio mean [mm] (st.dev.**
CEM III/A 42.5 LA	0.01202 (0.00068)	0.8643 (0.0126)
Fly ash	0.01949 (0.00105)	0.6787 (0.0247)
Sand 0/2	0.3114 (0.0205)	1.1463 (0.0822)
Sand 0/4	1.0259 (0.1275)	0.7794 (0.1114)
Coarse Aggregates	14.0771 (1.3259)	0.9183 (0.0605)

These characteristics (mean and standard deviation) can be used in order to investigate the influence of variations in the constituting materials on the water demand of the concrete mixture. Monte Carlo simulations were used in order to obtain random realizations of the water demand. Based on the data given in Table 5, 2000 random realizations are simulated for mean size and voids ratio of each of the constituting materials. Each set of these simulated values is then used to obtain a realization of the water demand, by using the method described in the previous paragraphs. The results of this simulation are given in Table 6, together with the results of simulations in case only the binder or sand or coarse properties are considered variable. Finally, Fig. 4 illustrates the obtained histogram of the water demand in case the properties of all constituents vary according to the data provided in Table 5.

Table 6: Mean value and standard deviation of the simulated water demand

Simulation	**Water demand mean [kg] (st. dev.**
Properties of all constituents are varying	169.8 (9.29)
Only properties of the binder are varying	170.4 (1.18)
Only properties of sand are varying	173.9 (5.81)
Only properties of coarse aggregates are	171.1 (7.29)

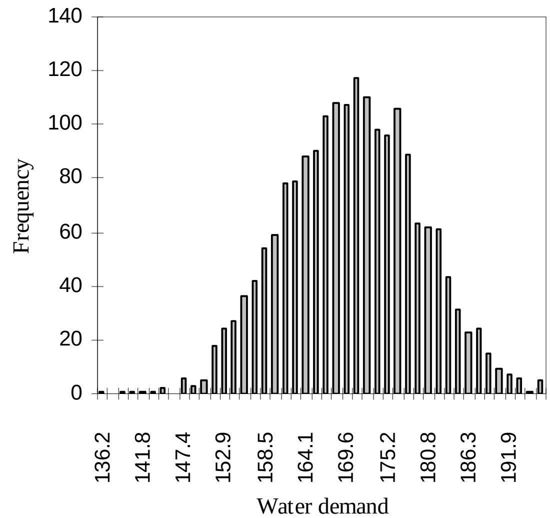

Fig. 4: Histogram of the simulated water demand in case the properties of all constituents are considered variable, with characteristics as described in Table 5

Further, also the effect of the variability in grain size distribution of the sand was investigated. Based on the specifications in the standards NBN B11-011 [6], NBN EN 12620 [7] and according to a "good" Belgian concrete sand [8][9], a numerical framework was developed to simulate random grain size distributions which fall inside the specified upper and lower boundary limits for the grain size distribution. The boundary limits of the investigated grain size distributions are illustrated in Fig. 5.

Again 2000 simulations of these random grain size distributions were calculated and the effect on the water demand was investigated by using the presented water demand prediction model. The results of these simulations are described in Table 7.

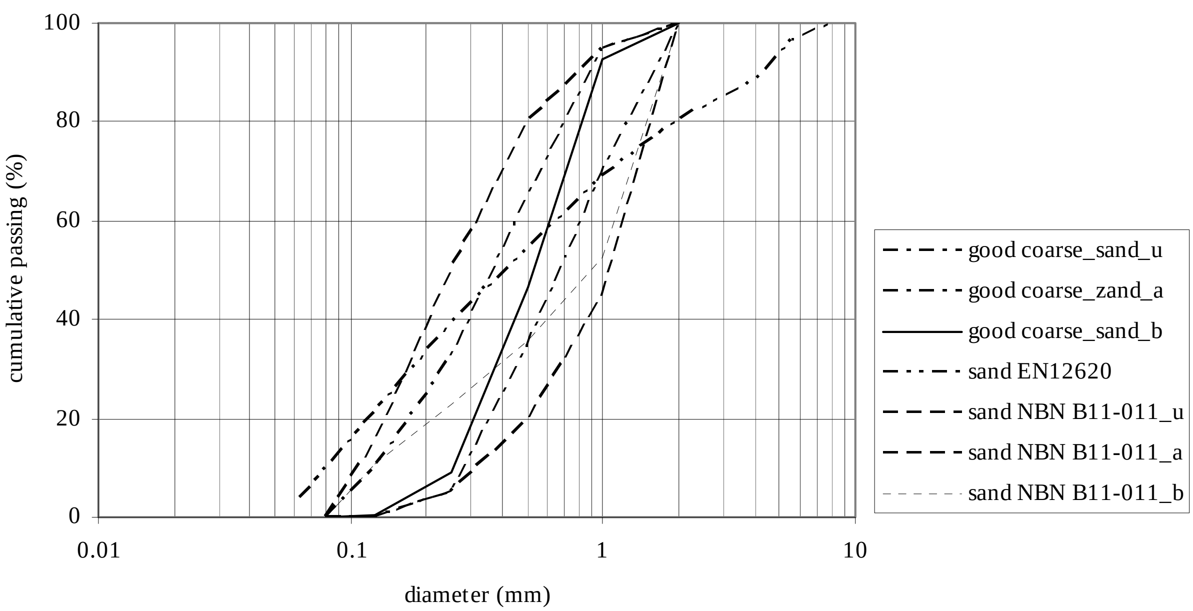

Fig. 5: Boundary limits for the grain size distributions of sands according the standards NBN B11-011 [6] and NBN EN 1620 [7] and a good Belgian sand [8]

Table 7: Mean value and standard deviation of the simulated water demand in case the variability in grain size distribution is considered

Simulation	**Water demand mean [kg] (st. dev.**
Sand according to NBN B11-	163.69 (8.78)
Sand according to EN 12620	184.9 (10.97)
“Good” concrete sand	166.5 (4.23)

These results clearly indicate the importance of stringent specifications on the acceptable grain size distributions. The results of these simulations can be compared with data from the concrete plant. Of course, no direct measurements of the actual water content are available. However, indirect information can be obtained by analyzing the concrete strength records. Based on the strength prediction model which was used at the plant, the variation of the strength results was translated into a variation of the water demand, yielding the results given in Table 8.

Table 8: Water demand of the concrete mixture based on strength records and the used strength prediction model

	Water demand mean [kg] (st. dev.
Actual variation of the water	173.5 (11.52)

Comparing the simulations with the actual water content, yields very comparable results. Furthermore, the magnitude of the variation in water demand based on the variability of all constituent materials is of the same magnitude as the variation in the actual water content.
Finally, it can be concluded that the water demand prediction methodology provides a useful tool for estimating the water demand as well as its variability and thus can be used as a more adequate steering tool for the design of concrete mixtures.

CONCLUSIONS

The simulated water demand (mean value) based on the varying properties (mean size and voids ratio) are comparable with the water demand obtained by the strength results, which means that the voids diagrams of Powers and the theory of the particle mixtures of Dewar provide a useful method for estimating the water demand of a concrete mixture.
The magnitude of the variation in water demand, based on the variability of all constituents, is of the same magnitude as the variation in the actual water content, which means that the variability of the properties of the raw materials is the main origin of the variability in water demand.
When the grain size distribution is considered as variable within the boundaries specified in the Standards, the simulated water demand and its variability indicate the need of more stringent specifications.

Further, the calibrated models can be used in order to predict the water demand for new mix designs and to predict the water demand when the raw materials parameters are changed. This consequently leads to a higher quality and more economic concrete production.

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